Chapter 12
Conservation Storage Yield

12-1. Introduction

a. Purpose. There are three purposes of this chapter: (1) to provide a descriptive summary of the technical procedures used in the hydrologic studies to analyze reservoirs for conservation purposes; (2) to furnish background information concerning the data requirements, advantages, and limitations of the various procedures; and (3) to establish guidelines which will be helpful in selecting a procedure, conducting the studies, and evaluating results.

b. Procedures. The procedures presented are generally used to determine the relationship between reservoir storage capacity and reservoir yield (supply) for a single reservoir. The procedures may be used to determine storage requirements for water supply, water quality control, hydroelectric power, navigation, irrigation, and other conservation purposes. Although the discussions are limited to single reservoir analysis, many of the principles are generally applicable to multi-reservoir systems. Chapter 4, “Reservoir Systems,” presents concepts regarding the analysis of a multi-reservoir system.

12-2. Problem Description

a. Determining storage yield relationships. The determination of storage-yield relationships for a reservoir project is one of the basic hydrologic analyses for reservoirs. The basic objective can be to determine the reservoir yield given a storage allocation, or find the storage required to obtain a desired yield. The determination follows a traditional engineering approach:

(1) Determine the study objectives. This includes the project purposes, operation goals, and the evaluation criteria.

(2) Determine the physical and hydrologic constraints for the site. This includes the reservoir storage and outflow capability, as well as the downstream channel system.

(3) Compile the basic data. The basic data include demands, flow, and losses. Also, the appropriate time interval for analysis, which depends on the data and its variations in time.

(4) Select the appropriate method, one that meets the study objectives and provides reliable information to evaluate results based on accepted criteria.

(5) Perform the analysis, evaluate the results, and present the information.

b. Evaluating hydrologic aspects of planning. Many of the methods described in other chapters of this manual are necessary to develop and provide data to evaluate the hydrologic aspects of reservoir planning, design, and operation. In many cases, the methods required to provide data for a reservoir analysis are more complex than the method for the reservoir study itself. However, because the usefulness and validity of the reservoir analysis are directly dependent upon the accuracy and soundness of basic data, complex methods can often be justified to develop the data.

c. General information. This chapter contains information on types of procedures, considerations of time interval, storage allocation, project purposes, several types of studies, and a summary of methods to analyze the results of reservoir studies. The methods can be characterized as simplified, including sequential and nonsequential analysis, and detailed sequential analysis. Emphasis is given to the sequential routing because:

(1) It is adaptable to study single or multiple reservoir systems.

(2) With an appropriate time interval, the variations in supply and demand can be directly analyzed.

(3) It gives results that are easily understood and explained by engineers familiar with basic hydrologic principles.

(4) The accuracy and results of the study can be closely controlled by the engineers performing and supervising the studies.

(5) It can be used with sparse basic data for preliminary analyses, as well as with detailed data and analyses.

12-3. Study Objectives

a. Establish and consider objectives. Before any meaningful storage-yield analysis can be made, it is necessary to establish and consider the objectives of the hydrologic study. The objectives could range from a preliminary study to a detailed analysis for coordinating reservoir operation for several purposes. The objectives, together with the available data, will control the degree of accuracy required for the study.

b. Determination of storage required. Basically, there are two ways of viewing the storage-yield relationship. The most common viewpoint involves the determination of the storage required at a given site to supply a given yield. This type of problem is usually encountered in the planning and early design phases of a water resources development study.

c. Determination of yield. The second viewpoint requires the determination of yield from a given amount of storage. This often occurs in the final design phases or in re-evaluation of an existing project for a more comprehensive analysis. Because a higher degree of accuracy is desirable in such studies, detailed sequential routings are usually used.

d. Other objectives. Other objectives of a storage-yield analysis include the following: determination of complementary or competitive aspects of multiple project development, determination of complementary or competitive aspects of multiple purpose development in a single project, and analysis of alternative operation rules for a project or group of projects. Each objective and the basis for evaluation dictates implicitly the method which should be used in the analysis.

12-4. Types of Procedures

a. Selecting. The procedures used to determine the storage-yield relationship for a potential dam site may be divided into either simplified or detailed sequential analysis. The selection of the appropriate technical procedure may be governed by the availability of data, study objectives, or budgetary considerations. In general, the simplified techniques are only satisfactory when the study objectives are limited to preliminary or screening studies. Detailed methods are usually required when the study objectives advance to the feasibility and design phases.

b. Simulation and mathematical programming analyses. The detailed sequential methods may be further subdivided into simulation analyses and mathematical programming analyses. In simulation analysis, the physical system is simulated by performing a sequential reservoir routing with specified demands and supply. In this type of study, attempts are made to accurately reproduce the temporal and spatial variation in streamflow and reservoir storage in a reservoir-river system. This is accomplished by accounting for as many significant accretions and depletions as possible. In mathematical programming analysis, the objective is to develop a mathematical model which can be used to analyze the physical system without necessarily reproducing detailed factors. The model usually provides a simulation that will provide a maximum (or minimum) value of the objective function, subject to system constraints.

c. Simplified method. A simplified method can be used if demands for water are relatively simple (constant) or if approximate results are sufficient, as in the case of many preliminary studies. However, it should be emphasized that the objective of the simplified methods is to obtain a good estimate of the results which could be achieved by detailed sequential analysis. Simplified methods consist generally of mass curve and depth duration analyses, which are discussed later.

d. Computer models. Computer models have changed the role of the simplified methods because of the relatively low cost of a detailed sequential routing. Computer programs like HEC-5 *Simulation of Flood Control and Conservation Systems* (HEC 1982c) provide efficient models of reservoirs, based on the level of data availability. For preliminary studies, minimum reservoir and demand information are sufficient. The critical and more complex problem is the development of a consistent flow sequence, which is required by all methods of analysis. Simplified methods still have a role in screening studies or as tools to obtain good estimates of input data for the sequential routings.

e. Detailed sequential routing. In the past, detailed sequential routings have been used almost exclusively for the development of operating plans for existing reservoirs and reservoir systems. However, the advent of the comprehensive basin planning concept, the growing demand for more efficient utilization of water resources, and the increasing competition for water among various project purposes indicate a need for detailed sequential routings in planning studies. Also, these complex system studies provide an opportunity to use optimization to suggest system operations or allocations (ETL 1110-2-336).

f. Mathematical programming. Mathematical programming (optimization) has generally been applied in water management studies of existing systems. The questions addressed usually deal with obtaining maximum gain from available resources, e.g., energy production from a hydropower system. Recent Corps applications include the review of operation plans for reservoir systems, e.g., Columbia and Missouri River Systems (HEC 1991d 1991f, and 1992a). These studies utilized the HEC Prescriptive Reservoir Model HEC-PRM (HEC 1991a).

g. Further information. Wurbs (1991) provides a review of modeling and analysis approaches including simulation models, yield analysis, stochastic streamflow models, impacts of basinwide management on yield, and optimization techniques.

12-5. Factors Affecting Selection

a. Examining objectives and data availability. Before initiating a storage-yield study, the study objectives and data availability should be examined in order to ascertain: (1) the method best suited for the study requirements; (2) the degree of accuracy required to produce results consistent with the study objectives; and (3) the basic data required to obtain the desired accuracy using the selected method. In preliminary studies, limitations in time and scope might dictate the data and method to be used and the accuracy. More detailed analyses are needed when a higher degree of accuracy is desired. A technical study work plan is very useful in organizing study objectives, inventory of available data, and the selection of general procedures.

b. Availability of data. The availability of basic physical and hydrologic data will quite frequently be a controlling factor in determining which of the several technical methods can be used. Obviously, the detailed methods require more data which may not be available. However, detailed simulation can be performed with limited system data if the historic flow data are available. The simplified methods require less data, but the reliability of the results decreases rapidly as the length of hydrologic record decreases. Therefore, it is often desirable to simulate additional hydrologic data for use with simplified methods. Hydrologic data and data simulation are discussed in Chapter 5.

c. Significant aspects. The study level and available data are not the only deciding factors. The study methods must capture the significant aspects of the prototype system. If simplified methods do not utilize data which have major influences upon the results, it would be necessary to utilize a more detailed method which accounts for variations in these data. For example, the National Hydropower Study (USACE 1979) used flow-duration techniques for most reservoirs, but used sequential routing for reservoirs with significant storage.

12-6. Time Interval

a. Selection. The selection of an appropriate time interval depends primarily on the type of analysis and the significance of the data variation over time. Time intervals of one month are usually adequate for nonsequential and preliminary sequential analyses. For more detailed studies, shorter routing intervals will ordinarily be required. Average daily flow data are increasingly used because they are readily available, and computer speed is sufficient to process the data in a reasonable time. Only in exceptional cases will routing intervals of less than one day be required for conservation studies. Considerable work is involved with shorter intervals, and the effects of time translation, which are usually ignored in conservation routing studies, become important with shorter intervals. Shorter intervals are necessary and should be used during flood periods or during periods when daily power fluctuations occur.

b. Using short time intervals. Ordinarily, when using short time intervals of one day or less, it is necessary to obtain adequate definition of the conditions under study. Periods selected for analysis should exhibit critical combinations of hydrologic conditions and demand characteristics. For example, analysis of hourly power generation at a hydroelectric plant under peaking conditions might be studied for a one-month period where extremely low flows could be assumed to coincide with extremely high power demands. As a rule, studies involving short time intervals are supplementary to one or more studies of longer periods using longer time intervals. The results of the long period study are often used to establish initial conditions such as initial reservoir storage for the selected periods of short-interval analysis.

c. Selecting a routing interval. In sequential conservation routing studies, the selection of a routing interval is dependent upon four major factors: (1) the demand schedule that will be utilized in determining the yield; (2) the accuracy required by the study objectives; (3) the data available for use in the study; and (4) the phase relationship between periods of high and low demands and high and low flow. If the water demand schedule is relatively uniform, it is ordinarily possible to estimate the amount of storage required for a specified yield by graphical analysis using the Rippl diagram or the nonsequential analysis discussed later herein. Demand schedules which show marked seasonal variations usually preclude the use of graphical techniques alone in determining storage requirements. This is especially true when the demand is a function which cannot be described in terms of a specific amount of water, as in the cases of hydroelectric power and water quality. In order to obtain accurate estimates of storage requirements when the demand schedule is variable, it is necessary to make sequential routing studies with routing intervals short enough to delineate important variations in the demand schedule. Simplified techniques may be utilized in obtaining a first estimate of storage requirements for the detailed sequential routing.

d. More accurate results. As a general rule, shorter routing intervals will provide more accurate results. This is due to many factors, such as better definition of relationships between inflow and releases, and better estimates of average reservoir levels for evaporation and power-head calculations. Average flow for longer routing intervals tends to reduce the characteristic variations of streamflows, thus producing a “dampened” storage requirement. This will tend to overestimate yield, or underestimate required storage for reservoirs with small storage. Therefore, the volume of conservation storage, compared to the average flow in a time period, is an additional consideration in selecting the time interval. For example, if a monthly interval is used and there is no sufficient conservation storage to control the variation of flow within the month, the use of average monthly will conceal that fact.

e. Effects on storage requirements. When fluctuations in streamflows or demands have a significant effect on storage requirements, computations should be refined for critical portions of the studies, or shorter routing intervals should be used. However, the routing interval should not be shorter than the shortest period for which flow and demand data are available. Attempts to “manufacture” flow or demand data are usually time consuming and may create errors or give a false impression of accuracy unless reliable information is available for subdivision of basic data.

f. Nonsequential methods. The selection of the flow interval for analysis by nonsequential methods is usually not as critical as for a sequential analysis. Because the nonsequential analysis is restricted to uniform demands, it does not produce results as accurate as those obtained by sequential methods. Therefore, there is very little gain in accuracy with short intervals. Flow intervals of one month are usually suitable for nonsequential methods.

12-7. Physical Constraints

Physical constraints which should be considered in storage-yield studies include conservation storage available, minimum pool, outlet capacities, and channel capacities. The addition of hydropower as a purpose will require the inclusion of constraints to power generation, e.g., maximum and minimum head, penstock capacity, and power capacity. If flood control is to be included as a project purpose, the maximum conservation storage feasible at a given site will be affected by the flood-control analysis.

12-8. Priorities

In order to determine optimum yield in a multiple-purpose project, some type of priority system for the various purposes must be established. This is necessary when the competitive aspects of water use require a firm basis for an operating decision. Safety of downstream inhabitants and cities are of utmost importance, which makes flood reduction the highest priority in a multiple-purpose project during actual operation. During periods of flood operations, conservation requirements might be reduced in order to provide the best flood operation. Although this chapter is not concerned directly with flood-control operation or criteria, it is necessary to integrate flood-control constraints with the conservation study to ensure that operating conditions and reservoir levels for conservation purposes do not interfere with flood-control operation. Priorities among the various conservation purposes vary with locale, water rights, and with the need for various types of water utilization. In multipurpose projects, every effort should be made to develop operation criteria which maximize the complementary uses for the various conservation purposes.

12-9. Storage Limitations

One of the reasons for making sequential conservation routing studies is to determine the effect of storage limitations on yield rates. Simplified yield methods cannot account for operational restrictions imposed by storage limitations in a multiple-purpose project. As shown in Figure 2-2, three primary storage zones, any or all of which may exist in a given reservoir project, may generally be described as follows:

- Exclusive capacity, generally for flood control, in the uppermost storage space in the reservoir.
- Multiple-purpose capacity, typically conservation storage, immediately below the flood control storage.
- Inactive capacity, or dead storage, the lowest storage space in the reservoir.

An additional space, called surcharge, exists between the top of the flood-control space and the top of the dam. Surcharge storage is required to pass flood waters over the spillway. The boundaries between the storage zones and operational boundaries within the zones may be fixed throughout the year, or they may vary from season to season as shown on Figure 12-1. The varying boundaries usually offer a more flexible operational plan which may result in higher yields for all purposes, although an additional element of chance is often introduced when the boundaries are allowed to vary. The purpose of detailed sequential routing studies is to produce an operating scheme and boundary arrangement which minimizes the chance of failure to satisfy any project purpose while optimizing the yield for each purpose. The three storage zones and the effect of varying their boundaries are discussed in the following paragraphs.

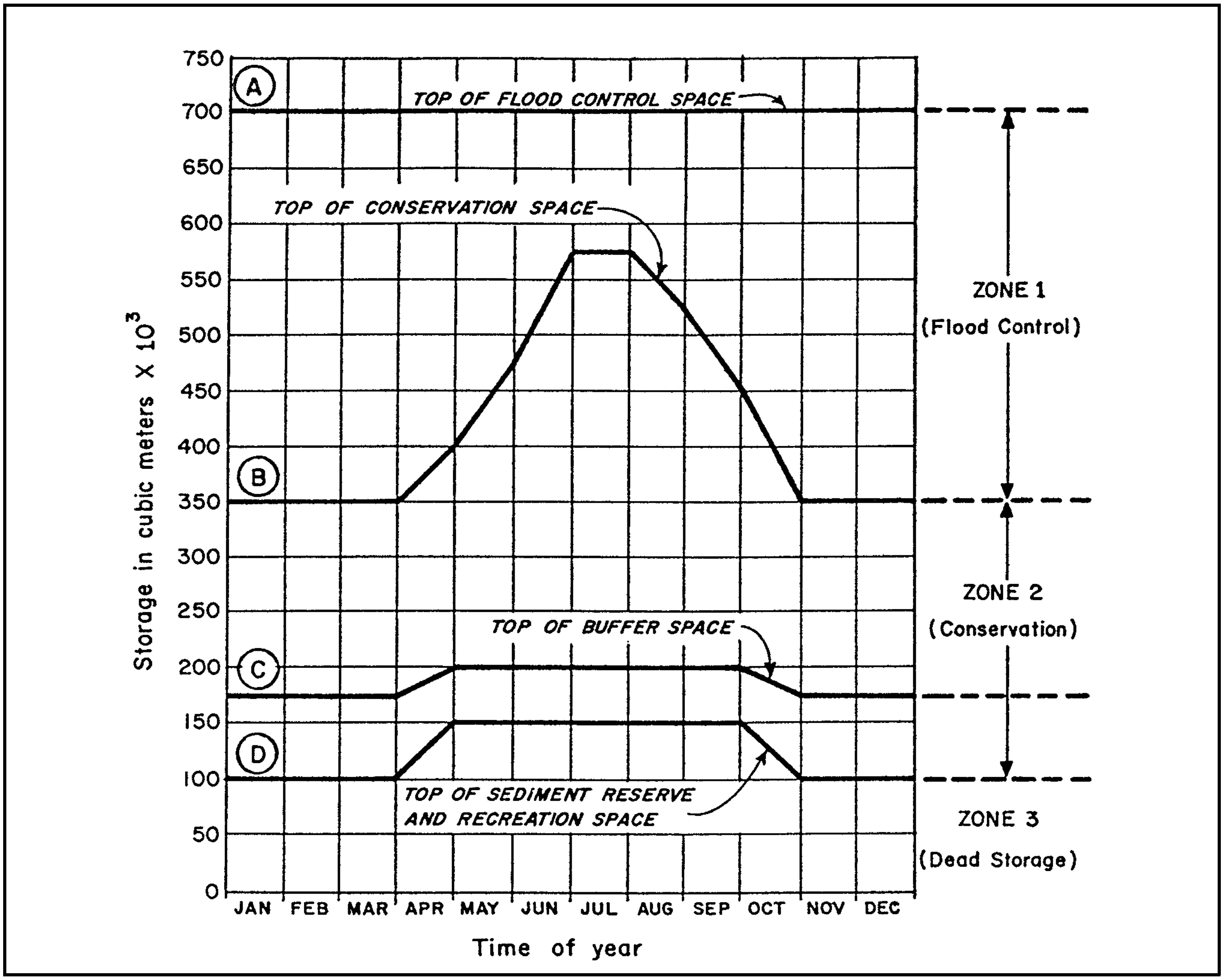

Figure 12-1. Seasonally varying storage boundaries

a. Flood-control storage. The inclusion of flood-control storage in a multiple-purpose project may adversely affect conservation purposes in two ways. First, storage space which might otherwise be utilized for conservation purposes is reserved for flood-control usage. Second, flood-control operations may conflict with conservation goals, with a resultant reduction or loss of conservation benefits. However, detailed planning and analysis of criteria for flood-control and conservation operations can minimize such adverse effects. Even without dedicated flood storage, conservation projects must be able to perform during flood events.

(1) Where competition between flood-control and conservation requirements exists, but does not coincide in time, the use of a seasonally varying boundary between flood-control storage and conservation storage may be used. The general procedure is to hold the top of the conservation pool at a low level when conservation demands are not critical in order to reserve more storage space for flood-control regulation. Then, as the likelihood of flood occurrence decreases, the top of the conservation pool is raised to increase the storage available for conservation purposes. Water management criteria are then tested by detailed sequential routing for the period of recorded streamflow. Several alternative patterns and magnitudes of seasonal variations should be evaluated to determine the response of the storage-yield relationship and the flood-control efficiency to the seasonal variation of the boundary. A properly designed seasonally-varying storage boundary should not reduce the effectiveness of flood-control storage to increase the conservation yield.

(2) Flood-control operation is generally simplified in conservation studies because the routing interval for such studies is frequently too long to adequately define the flood-control operation. Nevertheless, flood-control constraints should be observed insofar as possible. For example, channel capacities below the reservoir are considered for release purposes, and storage above the top of flood-control pool is not utilized.

b. Conservation storage. The conservation storage may be used to regulate minor floods in some multipurpose projects, as well as to supply water for conservation purposes. In addition to seasonal variations in its upper boundary between flood control and conservation, the lower conservation storage boundary may also vary seasonally. If several conservation purposes of different priorities exist, there may be need for a buffer zone in the conservation storage. The seasonal variation in the boundary between conservation storage and buffer zone would be determined by the relationship between seasonal demands for the various purposes.

c. Buffer storage. Buffer storage may be required for one or two reasons. First, it may be used in multipurpose projects to continue releases for a higher priority purpose when normal conservation storage has been exhausted by supplying water for both high and low priority purposes. Second, it may be used in a single-purpose project to continue releases at a reduced rate after normal conservation storage has been exhausted by supplying water at a higher rate. In either case, the boundary between the normal conservation storage and buffer storage is used to change the operational criteria. The location of this boundary and its seasonal variation are important factors in detailed sequential routing because of this change in water management criteria. The amount of buffer storage and, consequently, the location of the seasonally varying boundary between the buffer zone and the remainder of the conservation storage is usually determined by successive approximations in sequential routing studies. However, a simplified procedure, which produces a satisfactory estimate in cases without seasonally varying boundaries, is described in Section 12-11.

d. Inactive or dead storage. The inactive storage zone is maintained in the reservoir for several purposes, such as a reserve for sedimentation or for fish and wildlife habitat. As a rule, the reservoir may not be drawn below the top of the inactive storage. Although it may be possible to vary the top of the reserve pool as shown in Figure 12-1, it is seldom practical to do so. This could reflect the desire to maintain a higher recreation pool during the summer.

12-10. Effects of Conservation and Other Purposes

As previously indicated, the seasonal variation of demand schedules may assume an important role in the determination of required yield. The effect of seasonal variation is most pronounced when the varying demand is large with respect to other demands, as is often the case when hydroelectric power or irrigation is a large demand item. The quantity of yield from a specified storage may be overestimated by as much as 30 percent when a uniform yield rate is used in lieu of a known variable yield rate. Also, variable demand schedules often complicate the analysis of reservoir yield to the extent that it is impossible to accurately estimate the maximum yield or the optimum operation by approximate methods. Because detailed sequential routing is particularly adaptable to the use of variable demand schedules, every effort should be made to incorporate all known demand data into the criteria for routing. Thus, successive trials using detailed sequential analysis must often be used to determine maximum yield. Computer programs such as HEC-5 provide yield determination for reservoirs by performing the successive sequential routing until a firm yield is determined. *Firm yield* is the amount of water available for a specific use on a dependable basis during the life of a project. The project purposes which often require analysis of seasonal variations in demand are discussed in more detail in the following subparagraphs.

a. Low-flow regulation. The operation of a reservoir for low flow regulation at a downstream control point is difficult to evaluate without a detailed sequential routing, because the operation is highly dependent upon the flows which occur between the reservoir and the control point, called intervening local flow. As these flows can vary significantly, a yield based on long period average intervening flows can be subject to considerable error. A detailed sequential routing, in which allowance is made for variations of intervening flows within the routing interval, produces a more reliable estimate of storage requirements for a specified yield and reduces the chance of overestimating a firm yield. Ordinarily, the yield and the corresponding operation of a reservoir for low-flow regulation are determined by detailed sequential routing of the critical period and several other periods of low flow. The entire period of recorded streamflow may not be required, unless summary-type information is needed for functions such as power.

b. Diversion and return flows. The analysis of yield for diversions is complicated by the fact that diversion requirements may vary from year to year as well as from season to season. Furthermore, the diversion requirements may be stated as a function of the natural flow and water rights rather than as a fixed amount. In addition, diversion amounts may often be reduced or eliminated when storage in the reservoir reaches a certain critical low value. When any one of these three items is important to a given reservoir analysis, detailed sequential analysis for the entire period of flow record should be made to determine accurately the yield and the water management criteria. Coordination of the water management criteria for other purposes with the diversion requirements may also be achieved with the detailed sequential analysis results.

c. Water quality control. Inclusion of water quality control and management as a project purpose almost always dictates that sequential routing studies be used to evaluate project performance. Practically every variable under consideration in a water quality study will vary seasonally. Following are the variables which must be considered in a water quality study: (1) variation in quality of the inflow, (2) subsequent change in quality of the reservoir waters due to inflow quality and evaporation, (3) variation in quality of natural streamflow entering the stream between the reservoir and the control station, (4) variation in effluent from treatment plants and storm drainage outflow between the reservoir and the control station, and (5) variation in quality requirements at the control station. Accurate evaluation of project performance must consider all of these variations which pertain to water quality control. Additionally, there are several quality parameters which may require study, and each parameter introduces additional variations which should be evaluated. For example, if temperature is an important parameter, the level of the reservoir from which water is released should be considered in addition to the above variables. Likewise, if oxygen content is important, the effects of release through power units versus release through conduits must be evaluated.

d. Hydroelectric power generation.

(1) If hydroelectric power is included as a project purpose, detailed sequential routings are necessary to develop water management criteria, to coordinate power production with other project purposes, and to determine the project's power potential. As a rule, simplified methods are usable for power projects only for preliminary or screening studies, reservoirs with very little power storage, or when energy is a by-product to other operations. Flow-duration analysis, described in Chapter 11, is typically applied in these situations. Power production is a function of both head and flow, which requires a detailed sequential study when the conservation storage is relatively large and the head can be expected to fluctuate significantly.

(2) Determination of firm power or firm energy is usually based on sequential routings over the critical period. The critical period must consider the combination of power demand and critical hydrologic conditions. Various operational plans are used in an attempt to maximize power output while meeting necessary commitments for other project purposes. When the optimum output is achieved, a water management guide curve can be developed. The curve is based on the power output itself and on the plan of operation followed to obtain the maximum output. Critical period analysis and curve development are described in Section 12-11. Additional sequential routings for the entire period of flow record are then made using the rule curve developed in the critical period studies. These routings are used to coordinate power production with flood-control operation and to determine the average annual potential energy available from the project.

(3) In areas where hydroelectric power is used primarily for peaking purposes, it is important that storage requirements be defined as accurately as possible because the available head during a period of peak demand is required to determine the peaking capability of the project. An error in storage requirements, on the other hand, can adversely affect the head with a resultant loss of peaking capability.

(4) Tailwater elevations are also of considerable importance in power studies because of the effect of head on power output. Several factors which may adversely affect the tailwater elevation at a reservoir are construction of a reregulation reservoir below the project under consideration, high pool elevations at a project immediately downstream from the project under consideration, and backwater effects from another stream if the project is near the confluence of two streams. If any of these conditions exist, the resultant tailwater conditions should be carefully evaluated. For projects in which peaking operation is anticipated, an assumed “block-loading” tailwater should be used to determine reservoir releases for the sequential reservoir routing. The “block-loading” tailwater elevation is defined as the tailwater elevation resulting from sustained generation at or near the plant's rated capacity which represents the condition under which the project is expected to operate most of the time. Although in reality the peaking operation tailwater would fluctuate considerably, the use of block-loading tailwater elevation ensures a conservative estimate of storage requirements and available head.

(5) Reversible pump-turbines have enhanced the feasibility of the pumped-storage type of hydroelectric development. Pumped storage includes reversible pump-turbines in the powerhouse along with conventional

generating units, and an afterbay is constructed below the main dam to retain water for pumping during nongenerating periods. Sequential routing studies are required for analyses of this type because of the need to define storage requirements in the afterbay, pumping requirements and characteristics, and the extent to which plan should be developed. Many of the existing and proposed pumped-storage projects in the United States, however, are single purpose projects which do not have conventional units and often utilize off-channel forebays.

12-11. Simplified Methods

If demands for water are relatively constant or if approximate results are sufficient, as in the case of many preliminary studies, a simplified method can be used to save time and effort. The use of simplified techniques which do not consider sequential variations in streamflow or demand are generally limited to screening studies or developing first estimates of storage or yield. The following procedures will generally produce satisfactory results and continue to have a role in storage-yield determinations.

a. Sequential mass curve. The most commonly used simplified sequential method is the sequential mass curve analysis, sometimes referred to as the Rippl Method. This method produces a graphical estimate of the storage required to produce a given yield, assuming that the seasonal variations in demand are not significant enough to prohibit the use of a uniform draft (demand) rate. The sequential mass curve is constructed by accumulating inflows to a reservoir site throughout the period of record and plotting these accumulated inflows versus the sequential time period as illustrated in Figure 12-2.

(1) The desired yield rate, in this example 38,000 m^3/year, is represented by the slope of a straight line. Straight lines are then constructed parallel to the desired yield rate and tangent to the mass curve at each low point (line ABC) and at the preceding high point that gives the highest tangent (line DEF). The vertical distance between these two lines (line BE) represents the storage required to provide the desired yield during the time period between the two tangent points (points D and B). The maximum vertical difference in the period is the required

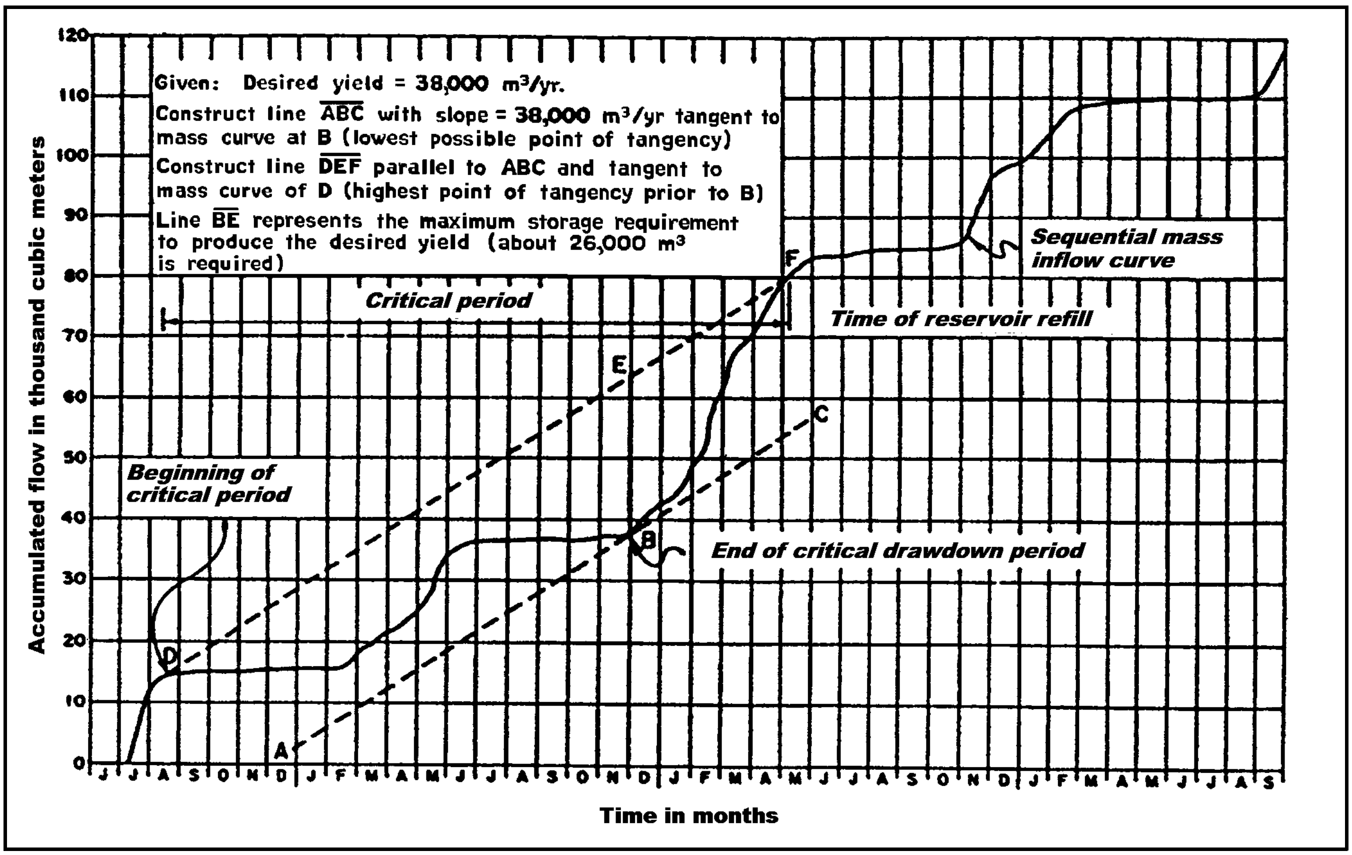

Figure 12-2. Storage determination using a sequential mass curve

storage to meet the desired yield, during the given flow sequence.

(2) The critical period is the duration of time from point **D**, when conservation storage drawdown begins, to point **F**, when the reservoir conservation storage fills. The critical drawdown is from point **D** to point **B**, while during the time from **B** to **F** the reservoir would be refilling.

(3) The sequential mass curve method does not indicate the relative frequency of a shortage. However, by using nonsequential methods, a curve of yield versus shortage frequency can be determined.

b. Nonsequential mass curve. Several nonsequential methods can be used to develop a relation for storage yield versus shortage frequency. The application of this procedure is limited, however, to water supply demands that are uniform in time. These methods involve the development of probability relations for varying durations of streamflow. The historical flows, supplemented by simulated flows where needed, are used to determine frequency tables of independent low-flow events for several durations. A series of low-flow events for a particular duration is selected by computing and arranging in order of magnitude, the independent minimum-flow rates for that duration for the period of record.

(1) After the frequency tables of independent low-flow events are computed for various durations, low-flow frequency curves are obtained by plotting the average flow on log-probability paper. Chapter 4 of EM 1110-2-1415 describes the procedure and presents an example table and frequency plot.

(2) Care must be exercised in the interpretation of the low-flow curves because the abscissa is “nonexceedance frequency per 100-years,” or the number of events within 100-years that have a flow equal to or less than the indicated flow. Thus, when low-flow durations in excess of one year are evaluated, the terminology cannot be used interchangeably with probability. For instance, during a 100-year period, the maximum number of independent events of 120 months (10-years) duration is 10. Therefore, the 120-month duration curve cannot cross the value of 10 on the “nonexceedance frequency per 100-year” scale.

(3) Minimum runoff-duration curves for various frequencies, as shown in Figure 12-3 are obtained by plotting points from the low-flow frequency curves on logarithmic paper. The flow rates are converted to volumes (millions of cubic meters in this example). The logarithmic scales simply permit more accurate interpolation between durations represented by the frequency curves.

(4) The nonsequential mass curve (Figure 12-4) is developed by selecting the desired volume-duration curve from Figure 12-3 and plotting this curve on arithmetic grid. The desired yield is then used to determine the storage requirement for the reservoir. The storage requirement is determined by drawing a straight line, with slope equivalent to the required gross yield, and by plotting this line tangent to the mass curve. The absolute value of the negative vertical intercept represents the storage requirement. The application of this procedure is severely limited everywhere in the case of seasonal variations in runoff and yield requirements because the nonsequential mass curve does not reflect the seasonal variation in streamflows, and the tangent line does not reflect seasonal variations in demand. However, the method does provide an estimate of yield reliability.

c. Evaporation losses. Another disadvantage of these simplified types of storage-yield analysis is the inability to evaluate evaporation losses accurately. This may not be critical in humid areas where net evaporation (lake evaporation minus pre-project evapotranspiration) is relatively small, but it can cause large errors in studies for arid regions. Also, these procedures do not permit consideration of seasonal variations in requirements, system nonlinearities, conflicting and complementing service requirements, and several other factors.

12-12. Detailed Sequential Analysis

a. Sequential analysis. Sequential analysis is currently the most accepted method of determining reservoir storage requirements. Many simplified methods have given way to the more detailed computer simulation approaches. In many instances, the computer solution provides more accurate answers at a lower cost than the simple hand solutions.

b. Accounting for reservoir water. Sequential analysis applies the principle of conservation of mass to account for the water in a reservoir. The fundamental relationship used in the routing can be defined by:

$$I - O = \Delta S \tag{12-1}$$

where

I = total inflow during the time period, in volume units

O = total outflow during the time period, in volume units

ΔS = change in storage during the time period, in volume units

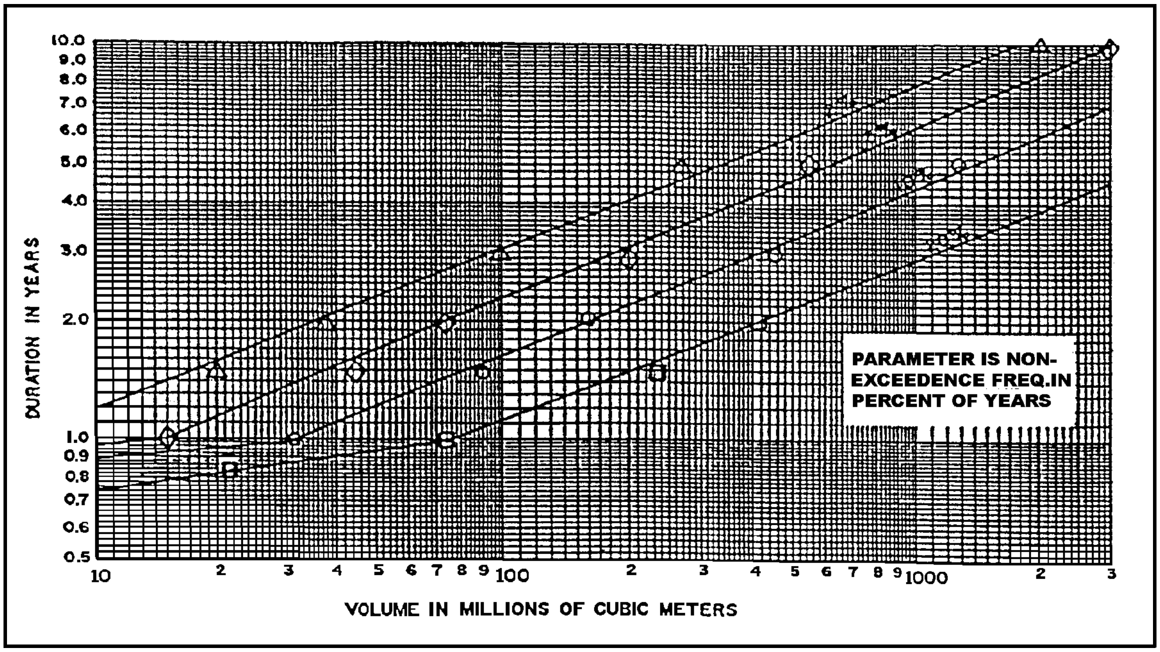

Figure 12-3. Minimum runoff-duration curves

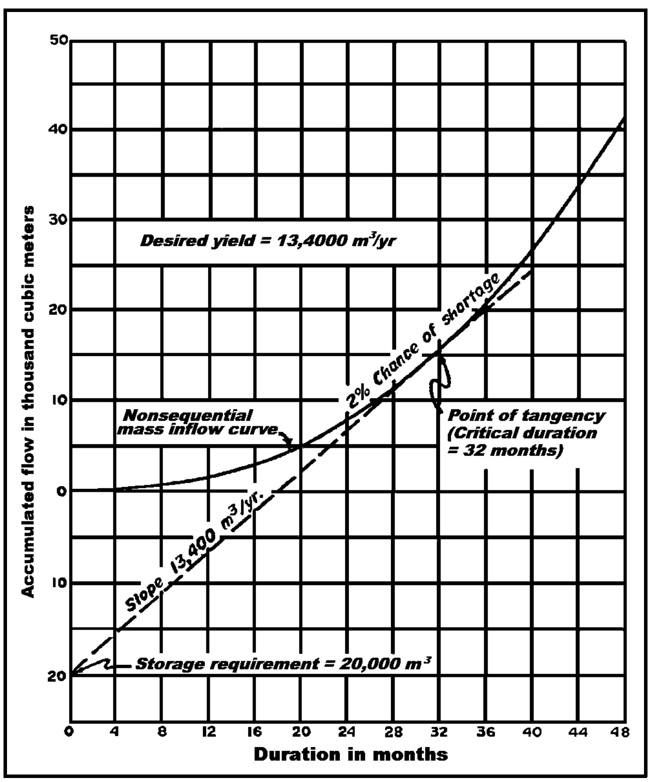

Figure 12-4. Nonsequential mass curve from Figure 12-3

The inflow and outflow terms include all types of inflow and outflow. The inflows should include natural streamflow, releases from upstream reservoirs, local inflow to the reservoir, precipitation falling on the reservoir surface (sometimes included in computation of net evaporation), and diversions into the reservoir. Outflows consist of reservoir releases plus evaporation losses, leakage, and diversions out of the reservoir. Sequential routing provided the framework for accounting for all water in the system. The application can be as detailed as required. The development of the required data constitutes the major effort in most sequential routing studies.

c. Sequential routing. Sequential routing uses a repetitive solution of Equation 12-1 in the form of:

$$S_t = S_{t-1} + I_t - O_t \tag{12-2}$$

where

S_t = storage at the end of time t, volume units

S_{t-1} = storage at the end of time t-1, volume units

I_t = average inflow during time step Δt, converted to volume units

O_t = average outflow during time step Δt, converted to volume units

The primary input includes reservoir storage capacity and allocation, requirements, losses, flow at all model locations for the simulation period, and system connectivity and constraints. The primary output for the reservoir is the average reservoir release for each time step and the resulting reservoir storage at the end of each time step. The releases are made to meet specified requirements, subject to all specified constraints such as storage allocation and maximum release capability. Downstream accounting of flows adds reservoir releases and subtracts diversions and losses to the local downstream flows to compute regulated flow at desired locations. If a short time interval is used, the flow travel time must be considered. Channel routing is usually done with hydrologic routing methods.

d. Multipurpose reservoir routings. The HEC-5 *Simulation of Flood Control and Conservation Systems* (HEC 1982c) computer program performs multipurpose reservoir routings for reservoir systems providing for services at the reservoirs and downstream control points. Releases from a reservoir are determined by the specified requirements for project purposes. Reservoir releases may be controlled at the dam site by hydroelectric power requirements, downstream control for flow, diversion, water rights, or quality. Additional diversions may be made directly from the reservoir.

(1) The program operates to meet the downstream flow requirement, considering available supplies and supplement flow from the intervening area. The storage allocation and most demands can be defined as constant, monthly varying, or seasonally varying. Historic simulations can be performed with period-by-period demands for low flow and hydropower.

(2) Computer program HEC-5 has a firm yield routine called optimization of conservation storage in the program user's manual. The routine can either determine the required storage to meet a specified demand or the maximum reservoir yield that can be obtained from a specified amount of storage. While designed for a single reservoir, it can use up to six reservoirs in a single run, provided the reservoirs operate independently. Optimization can be accomplished on monthly firm energy requirements, minimum monthly flow, monthly diversions, or all of the conservation purposes. The routine can estimate the critical period and make a firm yield estimate based on that period. After the firm yield is estimated, the program will perform a period of record simulation to ensure that the firm yield can be met. Several cycles of critical period and period of record simulations can be performed in one computer run, based on user input specifications.

12-13. Effects of Water Deficiencies

a. Water storages. Absolute guarantees of water yield are usually not practical, and the designer should therefore provide estimates of shortages that could reasonably develop in supplying the demands with available storage. If nonsequential procedures have been used, information on future shortages is limited to the probability or frequency of occurrence, and the duration or severity of shortages will not be known. In using the Rippl Method, the computations are based on just meeting the demand; therefore, no shortages are allowed during the period of analysis. The result gives no information on the shortages that might be expected in the future. Only in the detailed sequential analysis procedure is adequate information on expected future shortages obtainable.

b. Amount and duration of water shortage. The amount and duration of shortage that can be tolerated in serving various project purposes can greatly influence the amount of storage required to produce a firm yield. These tolerances vary a great deal for different project purposes and should be analyzed carefully in reservoir design. Also, changes in reservoir operation should be considered to meet needs during drought (HEC 1990a).

c. Intolerable shortages. Shortages are generally considered to be intolerable for purposes such as drinking water. However, some reduction in the quantity of municipal and industrial water required can be tolerated without serious economic effects by reducing some of the less important uses of water such as lawn watering, car washing, etc. Shortages greater than 10 percent may cause serious hardship. Most designs of reservoir storage for municipal and industrial water supply are based on supplying the firm yield during the most critical drought of record. Typically, drought contingency plans are developed to meet essential demands during drought conditions that may be more severe than the historic critical period. ETL 1110-2-335 provides guidance for developing and updating plans.

d. Irrigation shortages. For irrigation water supply, shortages are usually acceptable under some conditions. Often the desired quantity can be reduced considerably during the less critical parts of the growing season without great crop loss. Also, if there is a reliable forecast of a drought, the irrigator may be able to switch to a crop having less water requirements or use groundwater to make up the deficit. Shortages of 10 percent usually have negligible economic effect, whereas shortages as large as 50 percent are usually disastrous.

e. Water supply for navigation and low flow augmentation. In designing a reservoir to supply water for navigation or low-flow augmentation, the amount and duration of shortages are usually much more important than the frequency of the shortages. Small shortages might only require rescheduling of fully-loaded vessels, whereas, large shortages might stop traffic altogether. The same thing is true for such purposes as fish and wildlife where one large shortage during the spawning season, for example, could have serious economic effects for years to come.

f. Effects of shortages. Each project purpose should be analyzed carefully to determine what the effects of shortages will be. In many cases, this will be the criterion that determined the ultimate amount of reservoir storage needed for water supply and low-flow regulation.

12-14. Shortage Index

a. Definition. A general approach to shortage definition is to use a shortage index. The shortage index is equal to the sum of the squares of the annual shortages over a 100-year period when each annual shortage is expressed as a ratio to the annual requirements, as shown below:

$$SI = \frac{100 \sum_{i=1}^{i=N} \left[\frac{S_A}{D_A}\right]^2}{N} \tag{12-3}$$

where

SI = shortage index

N = number of years in routing study

S_A = annual shortage (annual demand volume minus annual volume supplied)

D_A = annual demand volume

This shortage index reflects the observation that economic and social effects of shortages are roughly proportional to the square of the degree of shortage. For example, a shortage of 40 percent is assumed to be four times as severe as a shortage of 20 percent. Similarly, as illustrated in Table 12-1, shortages of 50 percent during 4 out of 100 years are assumed four times as severe as shortages of 10 percent during 25 out of 100 years.

Table 12-1
Illustration of Shortage Index

Shortage Index	No. of Annual Shortages per 100 Years	Annual Shortage (S_A/D_A) In %
1.00	100	10
1.00	25	20
1.00	4	50
0.25	25	10
0.25	1	50

The shortage index has considerable merit over shortage frequency alone as a measure of severity because shortage frequency considers neither magnitude nor duration. The shortage index can be multiplied by a constant to obtain a rough estimate of associated damages.

b. Additional criteria needed. There is a definite need for additional criteria delineating shortage acceptability for various services under different conditions. These criteria should be based on social and economic costs of shortages in each individual project study, or certain standards could be established for the various services and conditions. Such criteria should account for degree of shortage as well as expected frequency of shortage.

12-15. General Study Procedures

a. Water supply. After alternative plans for one or more water supply reservoirs have been established, the following steps can be followed in performing hydrologic studies required for each plan:

(1) Obtain all available daily and monthly streamflow records that can be used to estimate historical flows at each reservoir and diversion or control point. Compute monthly flows and adjust as necessary for future conditions at each pertinent location. A review of hydrologic data is presented in Chapter 5.

(2) Obtain area-elevation data on each reservoir site to be studied and compute storage capacity curves. Determine maximum practical reservoir stage from physiographic and cultural limitations.

(3) Estimate monthly evapotranspiration losses from each site and monthly lake evaporation that is likely to occur if the reservoir is built.

(4) Determine seasonal patterns of demands and total annual requirements for all project purposes, if applicable,

as a function of future time. Synthesize stochastic variations in demands, if significant.

(5) Establish a tentative plan of operation, considering flood control and reservoir sedimentation as well as conservation requirements, and perform an operation study based on runoff during the critical period of record. The HEC-5 *Simulation of Flood Control and Conservation Systems* computer program can be used for this purpose.

(6) Revise the plan of operation, including sizes of various facilities, as necessary to improve accomplishments and perform a new operation study. Repeat this process until a near-optimum plan of development is obtained.

(7) Depending on the degree of refinement justified in the particular study, test this plan of development using the entire period of estimated historical inflows and as many sequences of synthetic streamflows and demands as might be appropriate. Methods for developing synthetic flow sequences are presented in Chapter 12 of the Hydrologic Frequency manual (EM 1110-2-1415).

(8) Modify the plan of development to balance yields and shortages for the maximum overall accomplishment of all project objectives.

b. Hydroelectric power. The study procedure for planning, designing, and operating hydroelectric developments can be summarized as follows:

(1) From an assessment of the need for power generation facilities, obtain information concerning the feasibility and utility of various types of hydroelectric projects. This assessment could be made as part of the overall study for a given project or system, or it could be available from a national, regional, or local power authority.

(2) From a review of the physical characteristics of a proposed site and a review of other project purposes, if any, develop an estimate of the approximate amount of space that will be available for either sole- or joint-use power storage. This determination and the needs developed under step (1) will determine whether the project will be a storage, run-of-river, or pumped-storage power project and whether it will be operated to supply demands for peaking or for baseload generation.

(3) Using information concerning seasonal variation in power demands obtained from the assessment of needs, and knowing the type of project and the approximate storage usable for power production, determine the historical critical hydro-period by review of the historical hydrologic data.

(4) An estimate of potential hydroelectric energy for the assumed critical hydro-period is made using Equation 11-2. If the energy calculated from this equation is for a period other than the basic marketing contract period (usually a calendar year), the potential energy during the critical hydro-period should be converted to a firm or minimum quantity for the contract period (minimum annual or annual firm in the case of a calendar year).

(5) Because the ability of a project to produce hydroelectric energy and peaking capacity is a complex function of the head, the streamflow, the storage, and operation for all other purposes, the energy estimate obtained in step (4) is only an approximation. Although this approximation is useful for planning purposes it should be verified by simulating the operation of the project for all authorized purposes by means of a sequential routing study. Chapter 11 provides methods for performing and analyzing sequential routing studies.

(6) From the results of detailed sequential routing studies, the data necessary for designing power-generating units and power-related facilities of the project should be developed. The design head and design output of the generating units, approximate powerhouse dimensions, approximate sizes of water passages, and other physical dimensions of the project depend on the power installation.

(7) Operation rules for the project must be developed before construction is completed. These rules are developed and verified through sequential routing studies that incorporate all of the factors known to affect the project's operation. For many multipurpose projects, these operation rules are relatively complex and require the use of computerized simulation models to facilitate the computations involved in the sequential routing studies.

(8) If the project is to be incorporated into an existing system or if the project is part of a planned system, system operation rules must be developed to define the role of the project in supplying energy and water to satisfy the system demands. These rules are also developed and tested using sequential routing studies. Sequential routing studies for planning or operating hydroelectric power systems are best accomplished using a computer program such as HEC-5.